Initial Study of Tube Networks for Flexible Airspace Utilization

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Air traffic in the United States is reaching new highs as it continues to increase at a steady pace. There is a general consensus that the National Airspace System needs to be transformed from today's rigid airways and airspace structure to a more flexible arrangement in order to accommodate and manage this growth. It has been suggested that one way to support this divergent growth in the mix of air traffic is to divide the airspace into different categories with different levels of service and entry requirements based on policy or price; e.g., connect high-traffic regions with a network of dedicated "tubes" analogous to the interstate highway system. This paper starts with today's air traffic as a baseline, groups airports into regions, and models a series of tubes connecting major regions. We achieve this grouping in two different ways, and present results based on the two methods. Next, we present simulation results by connecting these regions with a network of tubes. The modeling approach provides a basis for systematically studying the design and impact of dynamic airspace concepts in the National Airspace System.

I. Introduction

Air traffic in the United States is reaching new highs as it continues to increase at a steady pace. Although predicting future growth of traffic is difficult, there are two significant trends in the growth of air traffic demand. The heavily congested major airports will continue to see an increase in traffic. The second trend is the emergence of Regional Jets and other smaller aircraft with fewer passengers operating directly between non-major airports. There is a general consensus that the National Airspace System (NAS) needs to be transformed from today's rigid airways and airspace structure to a more flexible arrangement in order to accommodate this growth. The airspace and routes may be dynamically allocated to better accommodate traffic in the presence of convective weather, balance the workload in different regions and create efficient flow of traffic between different regions. In the future, it is conjectured that one way to support the divergent growth in the mix of air traffic is to divide the airspace into different classes with different levels of service and entry requirements based on policy or price. For example, the airspace could be divided into regions connecting major airports, regions with increased automation supporting aircraft separation and regions with low density of traffic where separation could be delegated to the aircraft. This change in the concept of operations from the current system will be accomplished in many steps. Many of the problems affecting the transformation from a homogeneous airspace to a more diverse airspace require the understanding and solution to the same issues. To focus on some of the issues, we consider the concept of "Generalized Tubes" – regions of high density traffic in the NAS connected by a system of dedicated routes – and examine the problem of designing such a network and report on some of its characteristics.

This paper starts with air traffic today as a baseline and analyzes the effect of dividing the airspace into a series of tubes connecting major airports analogous to the inter-state highways. We design a network connecting the top 18 regions and associate the top 250 busy airports with the appropriate region. This grouping is achieved in two different ways: (a) Weighted-Proximity Classifier (WPC) and (b) Clustering by Region Growing (CRG). Next, we compare the grouping characteristics and the percentage of total traffic captured by the two methods.

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The rest of the paper is divided into the following sections: Section II describes the concept of Tubes, some of the problems that need to be considered in its implementation, and an analysis of the baseline traffic pattern. Section III describes the two approaches to grouping the airports into regions and the relative merits of the two approaches. Section IV presents preliminary results on the impact of a network connecting the high density regions on the rest of the traffic. Section V presents a summary and concluding remarks.

II. Concept of Tubes

The concept of “a network of tubes” connecting high-density airports was introduced in Ref. 1. The idea is similar to the Interstate Highway System (IHS) in the United States with the Interstate Highway carrying the high-speed traffic and the local traffic being relegated to secondary roads. Ref. 2 explores the Tube concept by comparing current operations with a direct routing between New York and Chicago. Further, the Tube network was extended to include Philadelphia, San Francisco and Portland. We examine the Tube concept by creating a network connecting all the major airports in the United States. As in the design of the IHS, the Tube concept needs to address issues like the layout of the network, number of lanes in each link, protocols for entering and exiting from the network, workload, automation issues at on-ramps and off-ramps, and aircraft performance and equipage requirements. Some of the important issues that need addressing when constructing a network of tubes are:

1. Selection of high density regions: The NAS can be divided into regions ($R_1, R_{2,} ..., R_n$) of high density based on the population distribution and the traffic interconnecting these population centers. This problem is described in greater detail in the next section.
2. Connections between high density regions: Special lanes or tubes are established connecting Region I with Region J. If we have n regions, we could have as many as $n(n$-1) connections. These can be significantly reduced based on actual traffic patterns using network flow algorithms.
3. Control of traffic in the tubes: The traffic in the tube between two regions may have a number of lanes, passing lanes and bi-directional depending on the design. The number of lanes will also have an impact on the travel times between two regions, airport arrival and departure rates, and sector counts.
4. Merging of traffic from the airports in a region into the tube: The merging of traffic from different streams presents complex air traffic control situation and requires the development of algorithms to support both manual control and subsequent automation.
5. Distribution of traffic from the tube to the airports: this can be accomplished as a variation of the current procedures to distribute traffic from Jet routes to the airports similar to the FAA Playbook routes.
6. Complexity of traffic at merges and distribution points: The complexity of the traffic at these points and the amount of workload involved in controlling this traffic can be estimated by the Dynamic Density (DD) function. DD can be used as a criterion to limit the complexity of the merge points.
7. Benefits: The benefits of the Tube concepts needs to be evaluated at several levels to evaluate its operational feasibility.

A systematic study of the above problems is beyond the scope of this paper, but these problems will be addressed in subsequent studies. The rest of the paper is devoted to the selection of high density regions, a connection between these regions and a preliminary look at the changes to the traffic levels resulting from a version the tube concept.

Baseline Traffic Pattern

The design of the tube and its impact on the rest of the traffic will depend on the eligibility requirements to travel in the tube. We consider some of the factors affecting the design by analyzing the current traffic pattern in the United States. The FAA OPSNET (http://www.apo.data.faa.gov) database ranks the airports by the number of total tower operations. Further these operations are divided into itinerant and local operations. Table 1 shows the top-10 airports and the number of operations in each airport for January 15, 2005. The actual top-10 rank may vary from day to day. Figures 1 and 2 show the location of the top-30 airports and routes interconnecting the airports. Figure 3 shows the total number of operations and compares it to the traffic between the top-10, top-20 and top-30 airports on January 15, 2005. It is easy to infer from Figure 3 that the flow

Table 1. Number of operations for top-10 airports.

Rank	Number of Operations	Facility
1	2474	ATL
2	2319	ORD
3	1861	DFW
4	1680	PNE
5	1603	LAX
6	1482	RVS
7	1412	PHX
8	1407	IAD
9	1382	DEN
10	1338	LAS

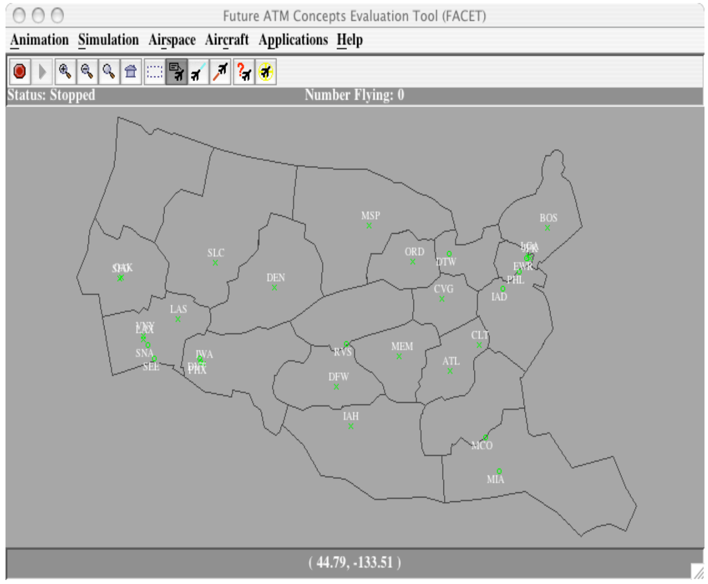

Figure 1. Location of the top-30 airports.

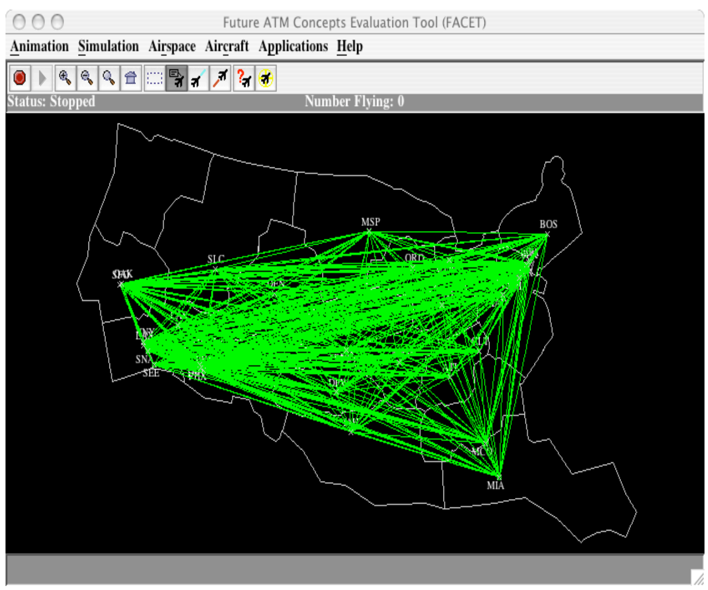

Figure 2. Routes interconnecting top-30 airports.

between major airports is a small percentage of the total traffic and for the tube concept to have a significant impact the tubes should connect regions of high density of traffic. There are several different ways airports can be clustered into groups to form regions and we consider to different approaches to achieve this in the next section.

III. Grouping of Major Airports

There are many methods and algorithms available to cluster objects into groups in Pattern Recognition and Computer Vision literature (Ref. 3 and Ref. 4). We consider two algorithms: (a) Weighted-Proximity classifier and (b) Clustering by region growing, with different properties to achieve the grouping and compare the results.

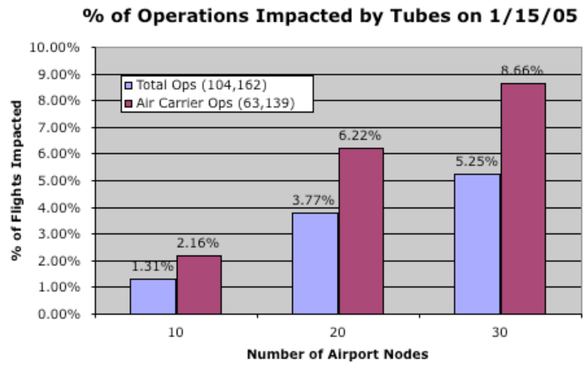

Figure 3. Operations involving traffic between major airports.

A. Weighted-Proximity Classifier (WPC)

Consider the top n-airports as the starting point. Each airport has a location (x_i, y_i); i=1,2,..n) and handles traffic T_i. Next, consider an airport not on the top-n list. Let ($x_{k,}y_k$) and T_k be the location and the traffic handled by the new airport. Assume, the new airport is closest to airport j. Then, the airports j and k form a group with a new location or centroid (x_l, y_l)and total traffic T_l where

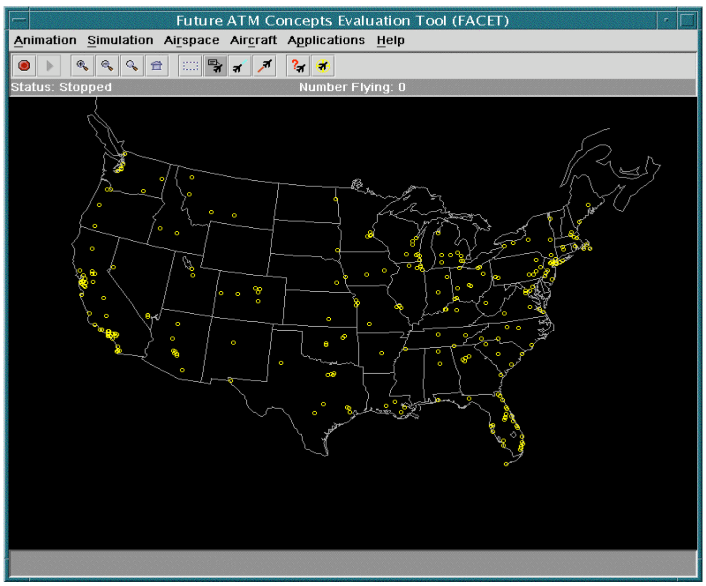

Figure 4. Location of the 250 airports.

$$T_l = T_i + T_k$$
$$X_l = (X_i * T_i + X_k * T_k)/T_l$$
$$Y_l = (Y_i * T_i + Y_k * T_k)/T_l$$

Next, reset $T_i = T_l$, $x_i = x_l$ and $y_i = y_l$ and repeat the operation until all the airports are assigned to one of the n groups.

B. Clustering by region growing (CRG)

Region growing is a popular method of grouping objects in Computer Vision. In general, there are three approaches: (a) local techniques: Objects are placed in clusters on the basis of their properties or the properties of their close neighbors, (b) global techniques: Objects are grouped into clusters on the basis of properties of large number of objects and (c) Splitting and merging techniques: Graph theory is used to split or merge groups starting from a finite number of groups and boundaries. For a given number of clusters, the inter-cluster and intra-cluster properties can be defined and the relation between properties can be used to grow or split clusters. The effectiveness of the grouping methodology depends to a large extent on the application area and the specific problem. Here, the cluster identification algorithm developed in Ref. 5 is used to compare the grouping results. The behavior of the region growing algorithm described in Ref. 5 varies considerably based on the selection of the threshold distance, d_c. A distance less than d_c is a property of all members of a group (cluster). The choice of d_c influences the number of resulting groups and the number of members in each group. Ref. 5 also presents an algorithm to determine the best value of d_c; it utilizes "natural neighbors" from Delaunay Triangulation and maximizes

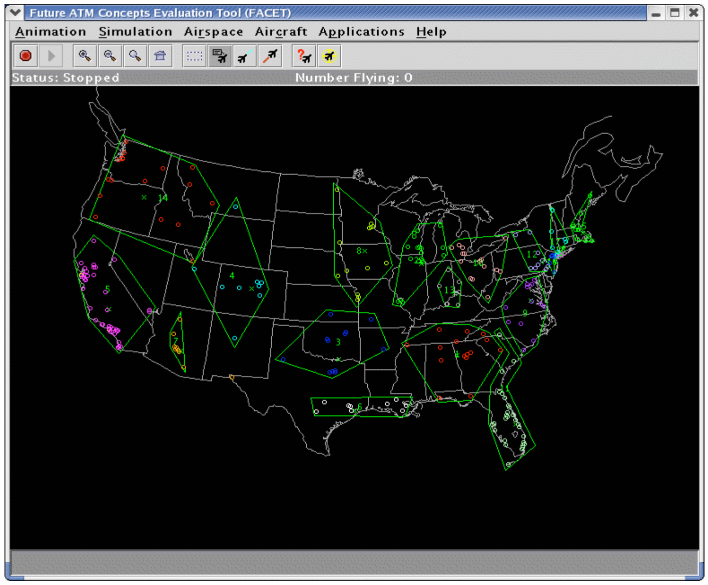

Figure 5 Clustering using weighted-proximity (WPC).

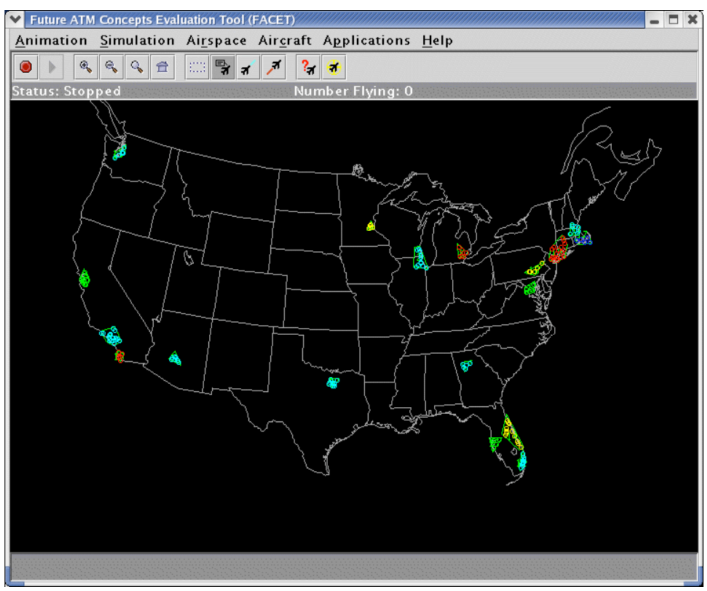

Figure 6. Clustering by region growing (CRG).

a performance metric to determine the best cluster patterns.

C. Clustering Results

Both algorithms are easy to implement. Fig. 4 shows the location of the top 250 airports. The number of groups in the WPC can be specified initially, whereas the number of groups results from the method described in Section IIIB above. In the CRG method, a large value of d_c resulted in a 1 to 4 regions grouping of all airports. Also, many airports were considered as background elements and were not included in the grouping. We adjusted the number of clusters in WPC to 18, the same as the CRG method generated. The clusters resulting from the WPC method are shown in Figures 5 and 6. Fig. 5 shows the 18 clusters and the locations of airports that are members of this cluster and the centroid of each region. Figure 7 shows the grouping results from the CRG method. Table 2 shows the 18 regions, the major airport in each region and the total number of operations covered by the groupings resulting from the WPC method. Table 3 shows similar results for the CRG method. As can be observed from Figures 5-8 and Tables 2 and 3, the grouping results produced by both methods can be used for further analysis of the Tube concept.

Table 2. Number of operations and % of total for the 18 clusters with WPC method.

Region	Airport	# Operations	% of total
1	ATL	216016	6.42
2	ORD	270912	8.05
3	DFW	166674	4.95
4	DEN	127565	3.79
5	LAX	499794	15.58
6	IAH	140636	4.18
7	PHX	129177	3.84
8	MSP	142220	4.23
9	CLT	176476	5.25
10	DTW	178245	5.30
11	CLT	367238	10.92
12	PHL	96905	2.88
13	CVG	109606	3.26
14	SLC	204617	6.08
15	BOS	126298	3.75
16	EWR	84392	2.51
17	LGA	90220	2.68
18	JFK	52106	1.55
		3122393	99.05
	Total Ops =	32073266	

Table 3. Number of operations and % of total for the 18 clusters with CRG method.

Region	Airport	# Operations	% of total
1	ATL	111161	3.30
2	ORD	171940	5.11
3	DFW	110483	3.28
4	LAX	216190	6.43
5	PHX	96868	2.88
6	MSP	76044	2.26
7	IAD	104828	3.12
8	DTW	72600	2.16
9	BOS	77111	2.29
10	EWR	220595	6.56
11	SEA	76528	2.27
12	MIA	110435	3.28
13	SFO	123813	3.68
14	MCO	108873	3.24
15	TPA	46581	1.38
16	SAN	59213	1.76
17	ACK	56104	1.67
18	ABE	25646	0.76
		1865013	55.43
	Total Ops =	32073266	

The CRG method produces regions that are small due to the selected $d_c$value, and included 55.43% of the total operations. The WPC method produced clusters covering larger regions and included 99.05% of the operations. It is interesting to note that the regions 1, 2 and 3, although different in appearance, produced by the two algorithms have the same major airports Atlanta (ATL), Chicago O'Hare (ORD) and Dallas-Fort Worth (DFW). We used the grouping resulting from the WPC method for subsequent analysis. The final version of the paper will include results based on the "best" pattern of CRG regions, determined by maximizing a performance metric that utilizes the number of airport operations.

IV. Impact of Tubes on Traffic Flow

We consider traffic flow on a typical day in the NAS and alter the flow using a version of the tube concept. As a baseline, we consider NAS performance on July 6, 2005 and use the simulation capability Future ATM Concepts

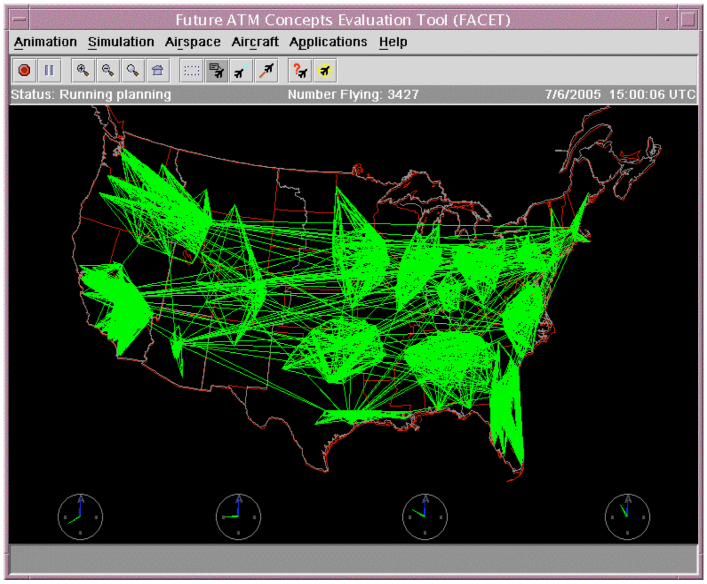

Figure 7. Interconnecting tubes between different regions.

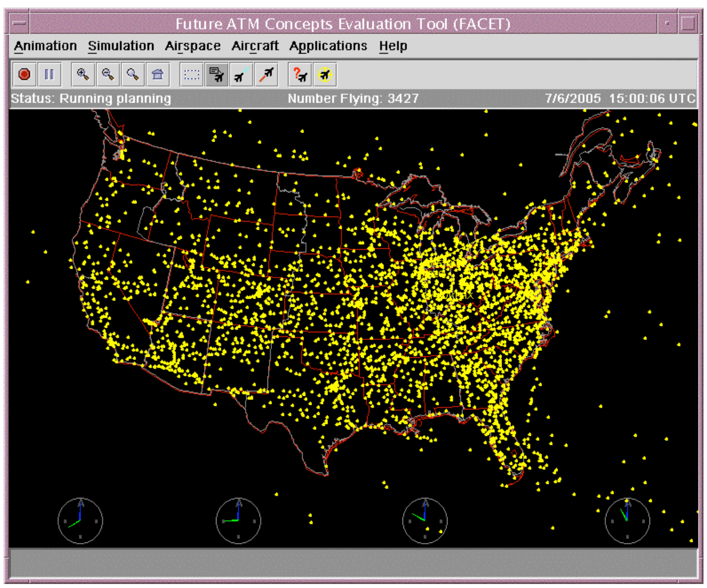

Figure 8. Aircraft in baseline simulation.

Evaluation Tool (FACET[6]) to compute the number of aircraft (a measure of traffic congestion) in different sectors of the NAS. The NAS is divided into 18 regions as outlined in Section III. In a simplistic implementation of the tube concept, all the 18 regions are interconnected to each other as shown in Fig. 7. This implementation is done by invoking the Playbook feature in FACET, which simulates the use of FAA's Severe Weather Avoidance Plans for aircraft flying between certain origin and destination airports or Centers, through specific routes. In later evaluations of the Tube concept, the number of interconnections between regions will be simplified by taking geography and the amount of traffic flow to eliminate and merge some of the interconnections using network flow algorithms. Fig 8. shows the location of various aircraft in baseline simulation. The aircraft impacted by the tube concept are shown in blue color in Fig. 9. Fig. 10 shows the traffic counts in selected sectors in different parts of the NAS. These sectors are chosen due to the amount and type of traffic (e.g. climbing, descending, overflight, etc.) that flows through their boundaries. As the tube concept changes the flow of traffic, Fig 11 shows the reduction in traffic(outlined by blue rectangles around the cells) ranging from two to seven in the selected sectors.

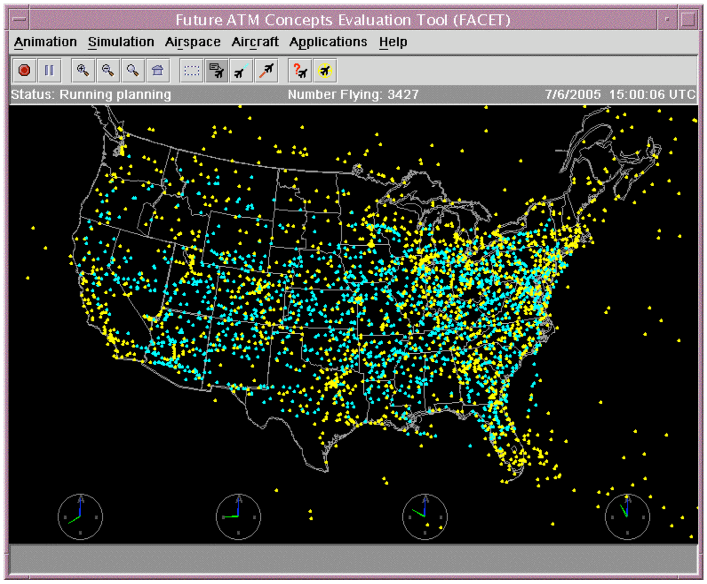

Figure 9. Aircraft affected by the layout.

Sector Counts (Inst. Max.) as of 15:00

Time	ZDV35	ZFW49	ZJX49	ZKC20	ZLA39	ZME23	ZOA33	ZLC45	ZDC50
Cap	20	20	17	17	16	18	18	23	18
15:00	12	9	17	12	11	7	17	9	22
15:15	15	9	13	15	11	7	13	10	20
15:30	15	8	14	15	12	11	14	18	20
15:45	11	7	11	15	13	9	19	18	19
16:00	10	9	12	11	9	9	12	16	18
16:15	12	10	11	11	9	8	13	16	21
16:30	10	11	11	10	7	11	15	12	14
16:45	7	12	14	6	15	16	19	14	14

Figure 10. Sector counts in baseline simulation.

Sector Counts (Inst. Max.) as of 15:00

Time	ZDV35	ZFW49	ZJX49	ZKC20	ZLA39	ZME23	ZOA33	ZLC45	ZDC50
Cap	20	20	17	17	16	18	18	23	18
15:00	12	9	17	11	13	6	18	9	20
15:15	14	9	9	12	10	5	10	9	15
15:30	13	7	9	13	7	9	11	15	13
15:45	9	3	7	9	9	5	14	16	16
16:00	9	9	9	9	7	2	10	16	19
16:15	12	8	10	15	7	4	14	11	21
16:30	11	7	10	15	9	6	14	10	14
16:45	6	6	8	9	7	12	17	13	14

Figure 11. Modified sector counts in tube simulation.

V. Conclusion

We have initiated a study a on the tube network concept, to analyze the different aspects in the evolution of the airspace from the current rigid sector and airways system to a more flexible airspace and route structure. Some preliminary results have been presented – more results will be included in the final version of the paper. The future dynamic airspace should support non-homogeneous airspace with different sets of rules for entry and an airspace, which can accommodate big changes in airspace due to convective weather or changes to strategic airspace.

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